Two-component stellar wind in hot stars

Jiří Krtička[1,2], Jiří Kubát[2]
[1] *Katedra teoretické fyziky a astrofyziky PřF MU, Kotlářská 2, CZ-611 37 Brno, Czech Republic*
[2] *Astronomický ústav AV ČR, CZ-251 65 Ondřejov, Czech Republic*

Abstract

We present the solution of hydrodynamic equations of radiatively driven stellar wind with inclusion of the frictional force. Hydrodynamic equations are solved for absorbing ions (the first component) and for a passive plasma (the second component). We discuss the critical point condition for such wind. We show that friction does not lead to the separation of the two components of the wind of hot stars. However, friction decreases the outflow velocity.

1 Introduction

Recent results of modeling of hot star winds indicated the possibility of a multicomponent nature of a wind with the low mass loss rate. Springmann & Pauldrach (1992) showed, that friction between absorbing ions and passive plasma (mainly hydrogen) leads to the heating of the plasma and to the decoupling of radiatively accelerated ions. Porter & Drew (1995) re-examined the semi-analytic model of the equatorial disc around Be-stars (so called wind-compressed disk – Bjorkman & Cassinelli (1993)). They showed that the inclusion of a frictional force leads to an enhancement of the equator-to-pole density contrast of a factor of 2. Moreover, Porter & Skouza (1999) pointed out the possibility of the presence of pulsating shells around stars with low-density radiatively driven wind.

Babel (1995) computed hydrodynamical model of a multicomponent wind of main sequence A star. However, this work was mainly intended to explain the existence of abundance anomalies in the atmospheres of chemically peculiar stars.

All these papers supported the idea that low-density radiatively driven winds may decouple at some point. We want show that this effect occurs in B stars only on a very moderate scale. For this class of stars friction leads to the lowering of the outflow velocity.

2 Model equations of a two component wind

assumptions

- passive plasma: hydrogen ions with mass equal to proton mass m_p and charge equal to proton charge q_p.
- absorbing ions: ions with mass $A_\mathrm{i} m_\mathrm{p}$ and charge q_i
- spherical symmetry
- wind temperature is equal to the effective temperature of the star

equations

- continuity equations

$$\frac{d}{dr}\left(r^2 \rho_\mathrm{p} v_{r\mathrm{p}}\right) = 0, \tag{1a}$$

$$\frac{d}{dr}\left(r^2 \rho_\mathrm{i} v_{r\mathrm{i}}\right) = 0, \tag{1b}$$

  - $v_{r\mathrm{p}}$, $v_{r\mathrm{i}}$: velocities of passive plasma and accelerated ions, respectively
  - ρ_p, ρ_i: densities of passive plasma and absorbing ions, respectively

- equations of motion (cf. Braginskij 1963)

$$v_{r\mathrm{p}} \frac{dv_{r\mathrm{p}}}{dr} = -f_\mathrm{p}^\mathrm{grav} + \frac{1}{\rho_\mathrm{p}} R_\mathrm{pi} - \frac{1}{\rho_\mathrm{p}} \frac{dp_\mathrm{p}}{dr}, \tag{2a}$$

$$v_{r\mathrm{i}} \frac{dv_{r\mathrm{i}}}{dr} = f_\mathrm{i}^\mathrm{rad} - f_\mathrm{i}^\mathrm{grav} - \frac{1}{\rho_\mathrm{i}} R_\mathrm{pi} - \frac{1}{\rho_\mathrm{i}} \frac{dp_\mathrm{i}}{dr}, \tag{2b}$$

  - p_p, p_i: partial pressures of each component
  - $f_\mathrm{p}^\mathrm{grav}$, $f_\mathrm{i}^\mathrm{grav}$: gravitational forces acting on each component,
  - $f_\mathrm{i}^\mathrm{rad}$: radiative force acting on absorbing ions (we assume no radiative force on passive plasma) following Castor et al. (1975)

$$f_\mathrm{i}^\mathrm{rad} = \frac{1}{\mathfrak{Y}_\mathrm{i}} \frac{\sigma_e L}{4\pi r^2 c} f \left(\frac{\rho_\mathrm{p}/\left(W m_\mathrm{p}\right)}{10^{11}\mathrm{cm}^{-3}}\right)^\delta k \left(\frac{\mathfrak{Y}_\mathrm{i}}{\sigma_e v_\mathrm{th} \rho_\mathrm{i}} \frac{dv_{r\mathrm{i}}}{dr}\right)^\alpha,$$

    force multipliers k, α, δ after Abbott (1982), f is the finite disk correction factor (Pauldrach et al. 1986), $\mathfrak{Y}_\mathrm{i}$ is the ratio of the ion density ρ_i to the hydrogen density ρ_p

  - R_{pi}: frictional force (per unit volume) acting between both components of the plasma after Springmann & Pauldrach (1992)

- boundary conditions:
  - fixed density ρ_{i} and ρ_{p} of both components at the base of the wind ($r = R_\star$)
  - at the base the velocities of each component are equal ($v_{r\mathrm{i}} = v_{r\mathrm{p}}$)

3 Critical points

Derivation of the critical point condition is similar to that pointed out by Abbott (1980) for the one component wind. Continuity and momentum equations are differentiated with respect to r and the coefficients of terms linear in derivatives with respect to r are collected to a matrix.

Critical points condition can be obtained by equaling of the determinant of the matrix to zero. Finally we obtain a condition of the form

$$\begin{vmatrix} \rho_{\mathrm{p}} & v_{r\mathrm{p}} & 0 & 0 & 0 & 0 & 0 & 0 \\ v_{r\mathrm{p}} & \frac{p_{\mathrm{p}}}{\rho_{\mathrm{p}}^2} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \rho_{\mathrm{i}} & v_{r\mathrm{i}} & 0 & 0 & 0 & 0 \\ 0 & 0 & v_{r\mathrm{i}} - \frac{df_{\mathrm{i}}^{\mathrm{rad}}}{dx} & \frac{p_{\mathrm{i}}}{\rho_{\mathrm{i}}^2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} = 0, \tag{3}$$

where $x = dv_{r\mathrm{i}}/dr$. It turns out that there are two critical points.

1. The critical point similar to that in thermally driven wind, which satisfies condition
$$v_{r\mathrm{p}}^2 = \frac{p_{\mathrm{p}}}{\rho_{\mathrm{p}}}. \tag{4}$$
2. Critical point given by the condition
$$v_{r\mathrm{i}} - \frac{p_{\mathrm{i}}}{\rho_{\mathrm{i}} v_{r\mathrm{i}}} - \frac{df_{\mathrm{i}}^{\mathrm{rad}}}{dx} = 0. \tag{5}$$
This is pretty the same condition known from one component radiatively driven winds. It is obvious, that once the condition (5) is met and velocities of both components of the wind are nearly equal, than final mass loss rate is just the same as for one component wind, but outflow velocity may be modified.

4 Numerical method

To solve hydrodynamic equations described here, we need a numerical method capable to solve the set of nonlinear coupled differential equations. We selected a slightly modified Henyey method (Henyey et al. 1964), which is nothing else than Newton-Raphson method applied to this problem. To handle the CAK critical point, we changed the boundary velocity at the base of the wind to fulfill the CAK singularity condition 5.

Set of linearized equations obtained in each iterative step is numerically solved using LAPACK library.

5 Calculations

Parameters of each main-sequence star for which we computed a model of the two component radiatively driven stellar wind are given in the Table 1. Stellar parameters T_{eff}, $\mathfrak{M}_\star$, $R_\star$ are taken from Harmanec (1988), wind parameters k, α, δ are taken from Abbott (1982). We selected carbon in an appropriate ionization stage as an average ion.

The above mentioned assumptions extremely simplify the problem, so our results should be considered as a qualitative description of the situation.

Table 1: Parameters of model stars

Stellar	Stellar parameters			Wind parameters			Average ion	
type	$\mathfrak{M}[\mathfrak{M}_\odot]$	$R_*[R_\odot]$	$T_{\mathrm{eff}}[\,\mathrm{K}]$	k	α	δ	$q_{\mathrm{i}}/q_{\mathrm{p}}$	A_{i}
O6	31.65	9.85	41 700	0.174	0.606	0.12	3.0	12.0
B0	14.57	5.80	29 900	0.156	0.609	0.12	2.0	12.0
B3	6.07	3.56	19 100	0.477	0.506	0.089	2.0	12.0
B4	5.12	3.26	17 200	0.365	0.509	0.105	2.0	12.0
B5	4.36	3.01	15 500	0.235	0.511	0.12	2.0	12.0
B6	3.80	2.81	14 100	0.275	0.517	0.106	2.0	12.0
B7	3.38	2.65	12 900	0.299	0.522	0.09	2.0	12.0
B8	2.91	2.44	11 600	0.327	0.529	0.07	1.8	12.0

6 Results

The results are shown in Figures 4–11. We plotted the run of the ion and hydrogen (passive plasma) velocities across the wind. The weak effect of decoupling can be seen in all figures displaying the wind velocity for later B stars. However, much more striking effect is the decrease of wind velocities with respect to the one-component solution. Both solutions are the same to some point r in the wind. At this point, the velocity gradients for both components (ions and hydrogen) start to decrease. Friction does not lead to any significant decoupling of the wind for hot stars, however it decreases the outflow velocity of the wind.

The reason of such a behavior may be indicated by inspection of Eqs.(2a) and (2b). Lowering of the friction force R_{pi} decreases the coupling between ions and hydrogen and, consequently, causes the slight difference between ion and hydrogen velocities.

The reason for the abrupt decrease of the velocity gradient is more subtle and is hidden in the nonlinear nature of equations of motion. Roughly speaking, if the abundance of ions is lower than that of hydrogen (as is our case), i.e. if $\rho_{\mathrm{p}} > \rho_{\mathrm{i}}$, then also $R_{\mathrm{pi}}/\rho_{\mathrm{p}} < R_{\mathrm{pi}}/\rho_{\mathrm{i}}$. Since $v_{r\mathrm{p}} \sim v_{r\mathrm{i}}$, it means that friction causes slightly larger changes of the nonlinear velocity term in the Eq. (2b). It may result in slight lowering the velocity gradient. Lower velocity gradient means also *lower radiative force*, consequently lower acceleration and even lower velocity gradient. The latter process finally almost stops the acceleration of the wind as can be seen especially for later B stars.

The radiative and frictional forces acting on the ionic component of a two-component wind model for O6 and B5 stars are plotted relative to the term $v_{r\mathrm{i}}\, dv_{r\mathrm{i}}/dr$ in Figure 3. There is a striking difference between runs of the relative force for a model of an O6 star wind and of a B5 star wind. The run of relative force in the model of the O6 star wind is strictly monotonic, however for the B5 star there is a maximum in the region, where ions are not capable to drive wind via friction. This maximum is caused mainly by lowering the velocity gradient.

If the above mentioned mechanism of reducing the effect of radiative acceleration of ions is correct, it may also reduce the inhibition effect (Owocki et al. 1996) of the wind compressed disk proposed by Bjorkman & Cassinelli (1993). This may make the wind-compressed disk more suitable for the explanation of disks around cool single Be stars. However, this must be supported by more sophisticated hydrodynamic calculations.

7 Conclusions

Our new simple hydrodynamic calculations show the effect of slowing down the wind of cool B stars by friction between radiatively accelerated ions and passive plasma. This effect is stronger for later B stars and weaker for earlier B stars. It is completely missing for O stars.

The reason why this effect was not found by other authors is straightforward. Springmann & Pauldrach (1992) computed only temperature structure of a two-component stellar wind and they did not compute any hydrodynamic model. Porter & Skouza (1999) calculated only parameters of hydrogen component of the wind with *fixed* velocity and density of ionic component. This approach was not self-consistent. Babel (1995) computed a self-consistent model of a two-component wind, but his research was restricted to A stars where other effect (element separation) are important.

Finally, we should mention the measurements of v_∞ for a large sample of stars by Lamers et al. (1995). They found a sudden drop of v_∞ near $T_{\text{eff}} = 21000\,\text{K}$ with respect to earlier stars. Note that we found the same trend in our simple calculations.

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